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13. ABSTRACT (Maximum 200 words)  The goal of this project has been to advance the state-of-the-art in performing fluid-structure interaction (FSI) simulations of parachute systems. This capability is being used by the Army to evaluate the dynamic behavior of new and existing airdrop systems. Airdrop systems have traditionally been designed using semi-empirical methods supplemented by extensive testing, which is time consuming and expensive. Computer simulation provides a cost effective alternative to this approach.  FSI simulations of airdrop systems require coupling of computational structural and fluid dynamics models. These simulations are very computationally intensive and therefore parallel computational methods are essential. Specifics objectives addressed under this project focused on both the structural mechanics and parallel requirements; the required fluid dynamics component has been performed collaboratively at Rice University under a separate effort.  The project accomplishments are classified into the following three general areas that are described in detail in this report: 1. Development of parallel structural algorithms required for FSI simulations 2. Development of new structural mechanics theory for modeling airdrop systems 3. Performance of large-scale computer simulations of Army airdrop systems			
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# **Advanced Structural Modeling for Fully Coupled Parachute Dynamics**

## **1. FORWARD**

The deployment, inflation, terminal descent and landing of a parachute system are extremely complex aerodynamic phenomena. These processes are governed by nonlinear time-dependent coupling between the parachute system and surrounding airflow, large canopy shape changes, and unconstrained motion of the parachute through the fluid medium. Due to these complexities, parachute systems have historically been designed using a semi-empirical approach supplemented by extensive testing. This approach to design is time-consuming and expensive.

During the last decade, the demands placed on parachute designers have increased significantly. Payload costs have increased, mission requirements have become more stringent, and the flight tests needed to develop new systems have become more costly. In light of these demands, the traditional semi-empirical approach to design is inadequate.

Computational methods have the greatest potential for providing engineers with the necessary predictive tools for parachute design. Although numerous commercial finite element codes exist, these codes lack the theoretical robustness needed for parachute simulations. Furthermore, these codes are closed to the users and therefore cannot be easily modified by the users for their specific needs.

Computer simulation of airdrop systems generally requires a Fluid-Structure Interaction (FSI) simulation that couples together Computational Structural Dynamics (CSD) and Computational Fluid Dynamics (CFD) models. The focus of this research project has been to develop an advanced CSD model for FSI simulations of current Army airdrop systems. This effort required the development of several new structural mechanics capabilities as well as development of new algorithms for large-scale parallel computing environments, which are described in this report. The CSD model is currently being used with a CFD model developed separately by researchers at Rice University to perform FSI simulations of Army airdrop systems.

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## **3. LIST OF APPENDIXES**

- Appendix A: Additional Results from Numerical Simulations

#### 4. PROBLEM STATEMENT

The primary goal of this project has been to develop an advanced Computational Structural Dynamics (CSD) model to accurately and efficiently perform Fluid-Structure Interaction (FSI) simulations of Army airdrop systems. To accomplish this, (1) several new mechanics capabilities were developed, and (2) new algorithms for large-scale parallel computing environments were developed. The following specific problems were addressed:

- FSI simulations of parachute systems require large-scale parallel computing. Implicit time integration schemes are preferable due to the long time duration associated with most parachute operations. To date, the vast majority of CSD parallel algorithms use explicit time integration. Therefore, efficient and accurate implicit algorithms for parallel FSI simulations were developed.
- Various contact phenomena commonly occur during the operation of parachute systems that can result in failure of the system to perform correctly. To date, the effect of contact in parachute systems is poorly understood and is difficult to study experimentally. Under the current project, parallel implicit contact algorithms were developed to simulate dynamic contact phenomena in airdrop systems.
- FSI simulations require both a CSD and CFD finite element mesh. For accurate modeling, the CFD mesh must follow the CSD mesh throughout the simulation as the parachute structure deforms. Therefore, for FSI simulations a mesh moving algorithm is required. In this project, a new mesh moving algorithm based on a “pseudo-solid” approach was developed for parachute FSI simulations.
- Pneumatic Muscle Actuators (PMAs) have recently been used as control devices in several new Army airdrop systems. Evaluation of the performance of these systems requires modeling of the true mechanical behavior of a PMA within a parachute structure. A new PMA element was developed that accurately models the mechanical behavior and can easily be incorporated within a general parachute finite element model.
- Controlled operation of parachute systems commonly involves feeding control lines dynamically through control points on the parachute. A good example is “slider reefing” where the parachute suspension lines pass through a fabric slider during inflation to control the inflation rate and forces. To address this type of problem, a special cable element was developed to solve the general problem of a cable string that is constrained to pass through a predefined moving point.
- The basic research performed under this project has been effectively transitioned to the Army. The results have been implemented into Army-owned computer codes that are used by various Army researchers to perform FSI simulations of Army airdrop systems.

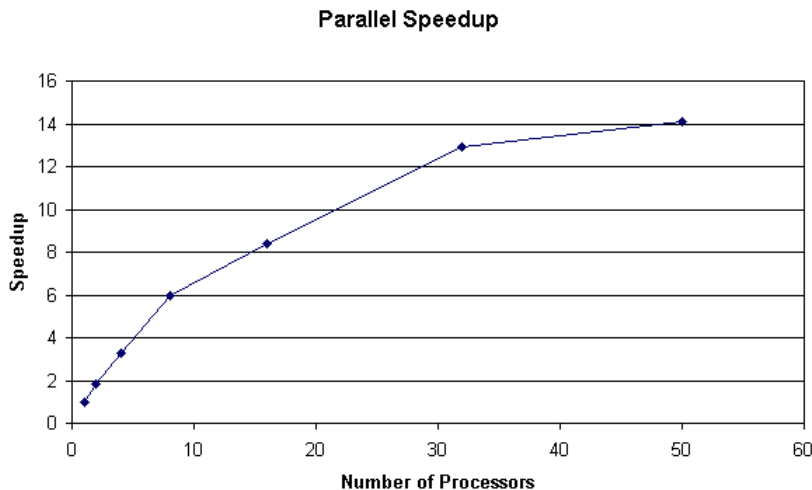
## 5. SUMMARY OF RESULTS

The primary result of this research project was the development of new mechanical models and parallel computing algorithms necessary to perform coupled FSI simulations of current Army airdrop systems. These basic research results were implemented in Army owned computer codes that have been used extensively by various researchers to perform FSI simulations of Army airdrop systems. During the performance of this basic research, the following specific results were also identified:

- *Efficient parallel contact algorithms based on implicit time integration schemes were developed for FSI simulations of airdrop systems.*

To date, the vast majority of parallel algorithms for geometrically nonlinear transient contact problems have been based on explicit time integration schemes (see, for example, Reference [1]). The time duration of contact phenomena in typical parachute applications is long which makes explicit methods infeasible. Furthermore, explicit methods do not check global equilibrium, which may result in global instabilities and/or inaccurate results. Although implicit methods are more computationally intensive, they provide unconditional stability and global equilibrium checking.

Special communication techniques were developed for parallel implicit contact algorithms that are not needed for explicit algorithms. An important test of parallel efficiency of these new algorithms is their speedup as a function of the number of processors. Figure 1 shows these results for a relatively large contact problem and indicates excellent speedup for the entire range of processors used. Additional details for this problem are given by Xu [2].



**Figure 1: Efficiency Evaluation of Parallel Implicit Contact Algorithms**

- *The penalty method combined with a “lumped” contact stiffness matrix provides an efficient and accurate implicit technique for modeling contact.*

Implicit time integration schemes for contact problems require the global contact stiffness matrix. One difficulty that arises is called “contact generated connectivity” (CGC) where new system connectivity is created when contact occurs that did not exist in the initial connectivity prior to contact. There are no addresses in the global stiffness matrix for CGC terms and they must be either neglected (this causes inaccurate results) or the addressing must be updated (this is computationally intensive). A second difficulty is ill-conditioning of the global stiffness matrix caused by using the penalty method for contact problems. This ill-conditioning significantly reduces the convergence rate of the iterative solver (GMRES) used to solve the system equations in parallel [3].

In this research project, a simple but highly effective technique was developed to eliminate both of these difficulties. Since the dominant term in the contact stiffness matrix is similar to a standard mass matrix, the concept of “lumping” the contact stiffness matrix was developed. A lumped contact stiffness matrix eliminates the problem of contact generated connectivity. A lumped contact stiffness matrix improves the diagonal dominance of the system equations and therefore always improves the convergence rate of iterative solvers. Numerical tests indicate that the use of a lumped contact stiffness matrix also produces accurate results [2].

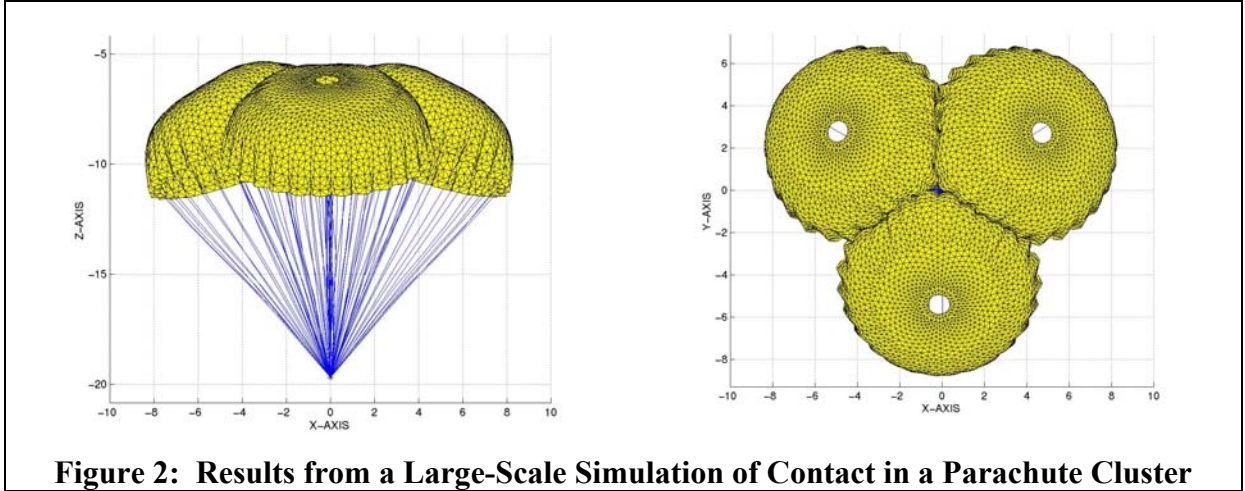
- *Large-scale parallel simulations provide an effective tool to study contact phenomena in airdrop systems.*

Large-scale simulations of contact events in parachute systems have not been previously presented by other researchers. In this project, several large-scale simulations were performed. These included (1) gore-to-gore contact during a round canopy inflation, (2) canopy-to-canopy contact in a parachute cluster, and (3) foreign body contact with an inflated canopy [2]. In general, the structural model and computer code performed very robustly during execution of these problems. Therefore, large-scale simulations are feasible for studying parachute contact phenomena. Figure 2 shows results for a large-scale simulation of contact within a three-canopy parachute cluster. The structural model contained over 18,000 degrees-of-freedom (DOF) and 13,000 elements and was executed for approximately 100,000 time steps.

- *Effective two-step mesh moving algorithms based on a “pseudo-solid” approach were developed by improving the criteria for element stiffening.*

For coupled FSI simulations, compatibility between the CSD and CFD meshes must be maintained. Since the structural model changes with time throughout the simulation, the fluid model must also change to maintain compatibility. In general, re-meshing of the CFD model is computationally intensive. Therefore, it is preferable to develop methods to move the CFD mesh that do not result in excessive element distortion. The majority of existing CFD mesh moving algorithms are based on a pseudo-solid approach. In this approach, the CFD volume is treated as a linear elastic pseudo-solid material with

prescribed displacement boundary conditions corresponding to the structural mesh motion. The resulting displacements of the pseudo-solid model are then used to move the CFD mesh.

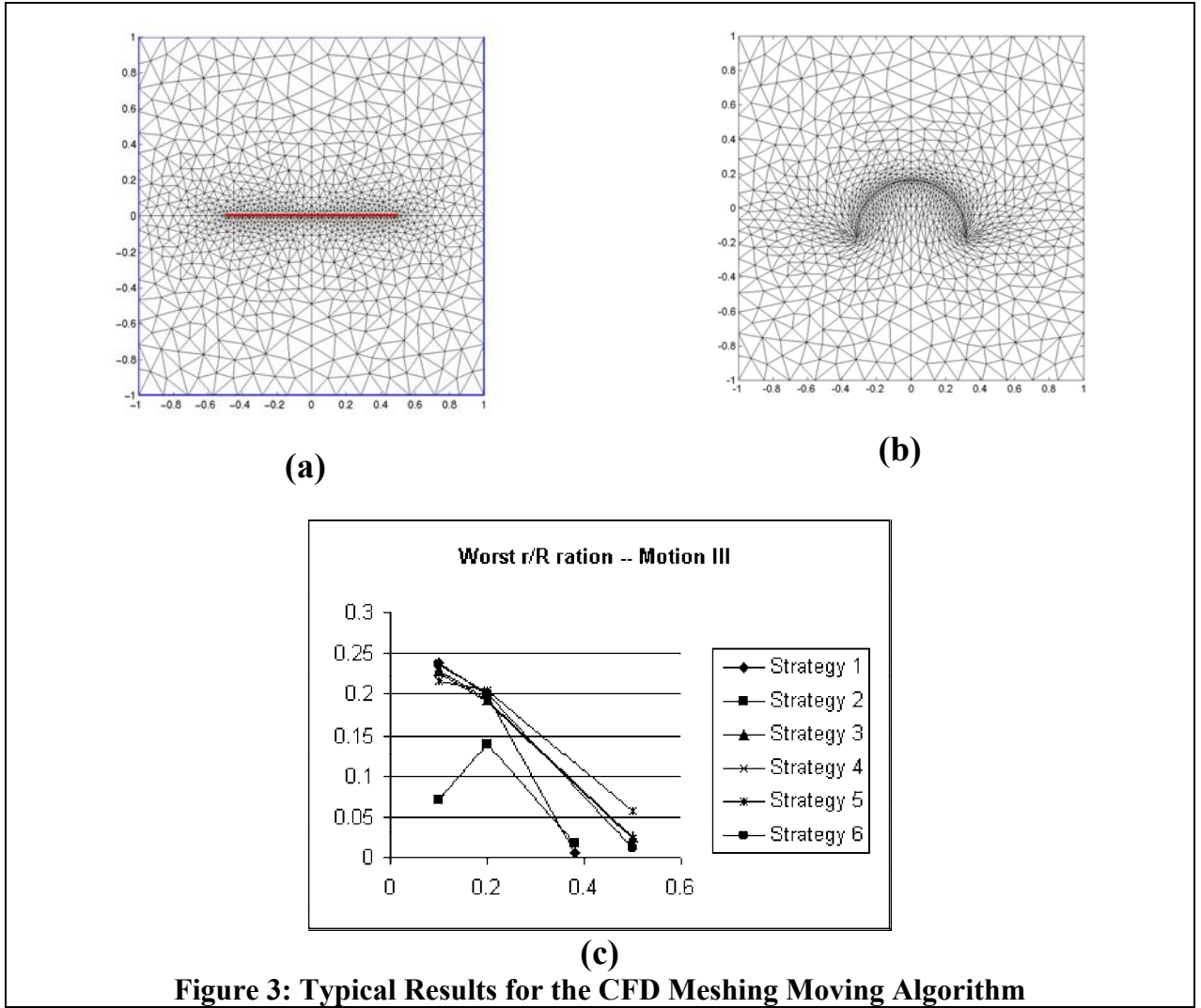


In general, the mesh motions associated with parachute simulations can be quite large and, therefore, robust algorithms are required to maintain the integrity of the CFD mesh. In the current project, a two-step (predictor-corrector) method was developed with new criteria for selecting the pseudo-solid properties. These included (1) stiffening based on compression versus tension, (2) use of a negative Poisson's ratio, and (3) removal of deviatoric stresses [2].

Typical results are shown in Figure 3. Figure 3a shows the initial configuration of the CFD mesh. Figure 3b shows the CFD mesh after successfully moving the mesh using the new pseudo-solid method. Figure 3c is a plot of mesh quality (worst element aspect ratio) versus magnitude of mesh motion for several state-of-the-art mesh moving algorithms (Strategies 1, 2, 3 from References [4] and [5]) and the new algorithms developed in this project (Strategies 4, 5, 6 from Reference [2]). Based on this criterion, it can be seen that the mesh moving algorithms developed under this project yield better results than other mesh moving algorithms for this particular problem. Additional examples of the new mesh moving algorithm are given by Xu [2].

- *An accurate and efficient element was developed for modeling the mechanics of Pneumatic Muscle Actuators (PMAs).*

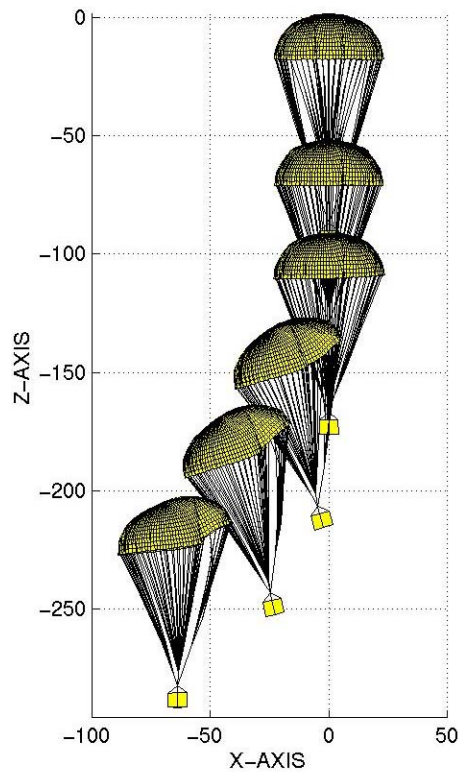
Pneumatic Muscle Actuators (PMAs) have recently been used as control devices in several new Army airdrop systems. These include (1) a soft-landing airdrop system, and (2) a low cost steerable airdrop system [6, 7]. In general, the relationship between PMA internal pressure, length, and force is nonlinear. A new PMA model was needed to facilitate the simulation of new airdrop systems that contain PMAs.



The new PMA element is a straight, two-node, line element with three displacement DOF per node that can easily be used in a general parachute structural model. The element is based on a Total Lagrangian formulation and is suitable for geometrically nonlinear, dynamic analysis. The PMA mechanics is formulated by assuming that the PMA fibers are inextensible [8]. This assumption has been shown to be very accurate for typical PMAs [9].

Figure 4 shows application of the PMA elements for modeling the Affordable Guided Airdrop System (AGAS), which is a new actively controlled steerable parachute system [7]. In this system, the four risers are PMAs. By changing the PMA pressures, the lengths of the risers are changed, causing reorientation of the canopy and redistribution of canopy pressure, which results in a controllable steering of the system. Figure 4 shows the system configuration at several times during a steering maneuver.





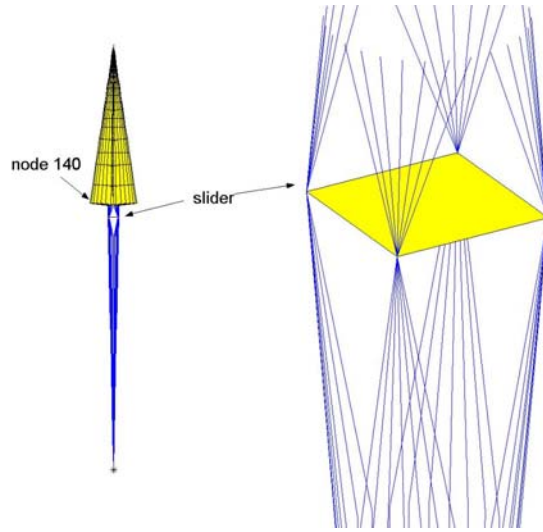
**Figure 4: Application of PMA Elements for Simulation of AGAS**

- *A new “Sliding Cable Element” was developed for parachute simulations involving a cable string passing through a moving point.*

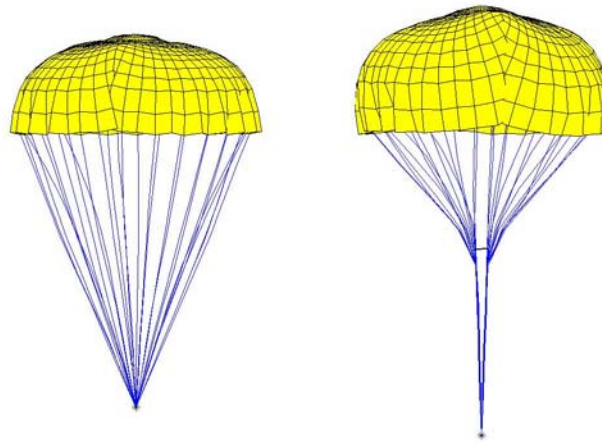
A new class of elements, called Sliding Cable Elements (SCE), was developed to model the generic problem of a cable string that passes dynamically through a moving point. This capability is needed to model typical parachute operations where control lines are fed dynamically through rings or grommets to achieve a specific goal. The SCE is a three-node bilinear element with three displacement DOF per node that can easily be included in a general parachute structural model. The element is based on a Total Lagrangian formulation and is suitable for geometrically nonlinear, dynamic analysis.

A good example is “slider reefing” of a parachute system, which is a common technique used to reduce the rate of inflation of a parachute canopy [10]. A typical “slider” consists of a square piece of fabric with grommets at each corner. The parachute suspension lines are divided into four groups that are each threaded through one grommet. Prior to inflation, the slider is positioned at the top of the suspension lines near the canopy skirt. During inflation, the canopy opens and forces the slider to move downward along the suspension lines. In general, the resistance of the slider reduces the canopy inflation rate, which is the desired effect.

Figure 5 shows the application of SCE to simulation of the inflation of a parachute with slider reefing. Figure 5a shows the initial folded configuration of the parachute (left) and the groups of suspension lines passing through the corners of the slider (right). Figure 5b shows a comparison of partially inflated, identical parachutes without the slider (left) and with a slider (right) at the same time. It is quite evident in the simulation results that the slider causes a significant reduction in the inflation rate. Additional applications of SCE to parachute systems are given by Zhou [8].



(a)



(b)

**Figure 5: Application of Sliding Cable Elements to Parachute Slider Reefing**

## • PUBLICATIONS

### Ph.D. Dissertations

Zhenlong Xu, “Parallel Finite Element Methods for Modeling Contact in Geometrically Nonlinear Membrane Structures,” Ph.D. Dissertation, University of Connecticut, August, 2002.

### Masters Theses

Bo Zhou, “Development of a Pneumatic Muscle Actuator Element and a Sliding Cable Element for Parachute Simulations,” Masters Thesis, University of Connecticut, August, 2002.

### Journal Articles

Zhenlong Xu, Michael Accorsi, and John Leonard (2002), "Parallel Contact Algorithms For Nonlinear Implicit Transient Analysis," Computer Methods in Applied Mechanics and Engineering (in review).

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K. Stein, R. Benney, V. Kalro, T. Tezduyar, J. Leonard and M. Accorsi (1999) "3-D Computation of Parachute Fluid-Structure Interactions: Performance and Control," 15<sup>th</sup> CEAS/AIAA Aerodynamic Decelerator Systems Technology Conference, June, 1999, Toulouse, France.

## **7. SCIENTIFIC PERSONNEL**

- Principal Investigators

Professor Michael L. Accorsi, University of Connecticut  
Professor John W. Leonard, University of Connecticut

- Graduate Students (Degree & Completion Date)

Zhenlong Xu (Ph.D. August 5, 2002)  
Bo Zhou (M.S. August 5, 2002)

- Collaborators

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Professor Keith Stein, Bethel College, St. Paul, MN.  
Professor Tayfun Tezduyar, Rice University, Houston, TX.

## **8. INVENTIONS**

- No inventions were conceived during this research project.

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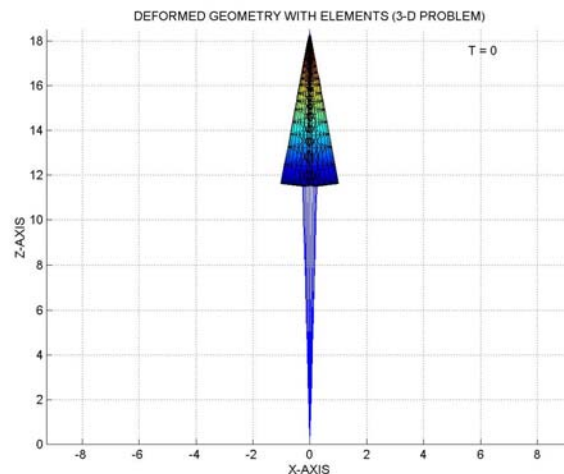
## 10. APPENDIX A: Additional Results from Numerical Simulations

This appendix briefly describes additional results from numerical simulations that were performed using the advanced Computational Structural Dynamics (CSD) model developed under this project. Additional details are available in References [2] and [8].

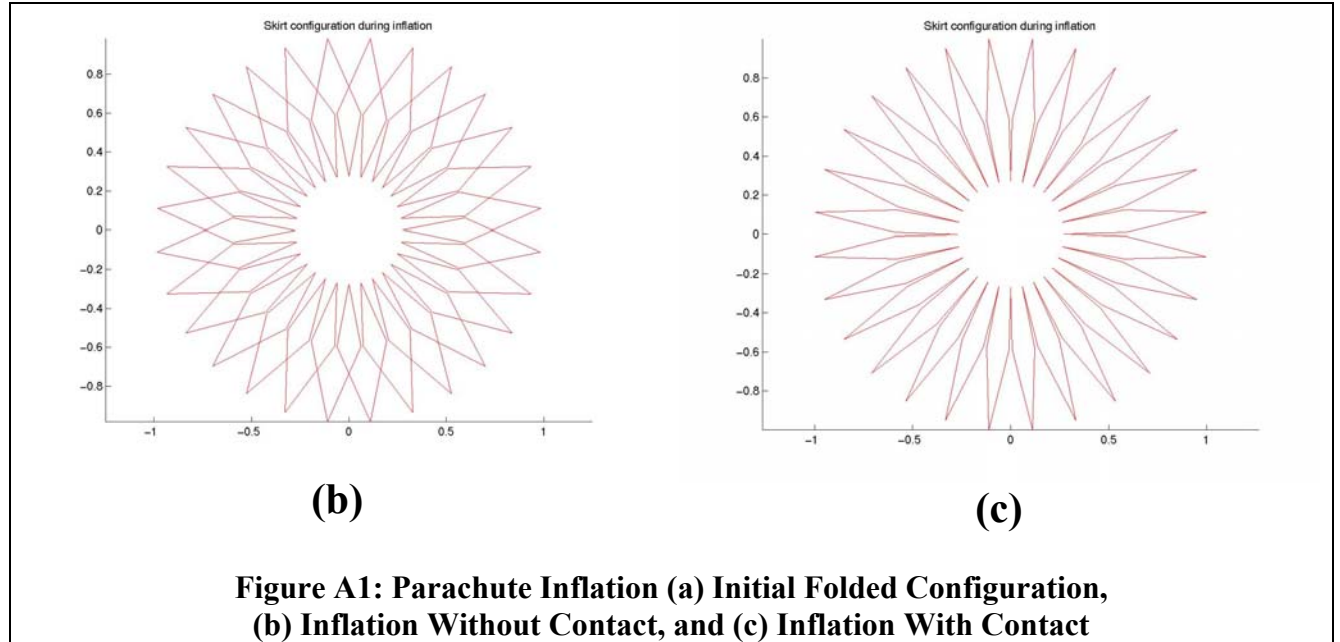
- **Simulation of Contact During Inflation of a Round Canopy**

In this simulation, a round canopy is inflated from the initially folded configuration shown in Figure A1a. Figure A1b shows the canopy skirt perimeter during inflation for a simulation that did not model contact. It is apparent that this simulation is not realistic since the results exhibit significant overlapping of adjacent gores. Figure A1c shows the skirt perimeter for a simulation that includes modeling of contact. These results show that overlapping of gores is effectively prevented by the contact algorithms, and are therefore expected to be more realistic.

The CSD model provides an effective tool for modeling contact during parachute inflation. This is significant because the failure of a parachute to unfold and inflate represents an extremely dangerous occurrence.

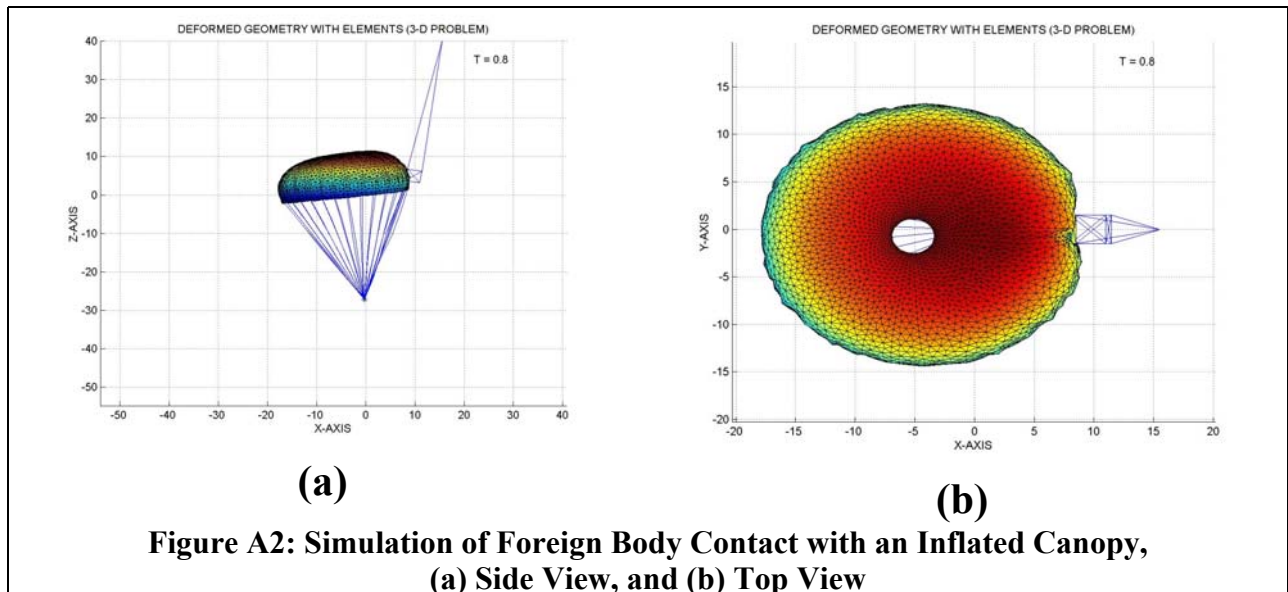


**(a)**



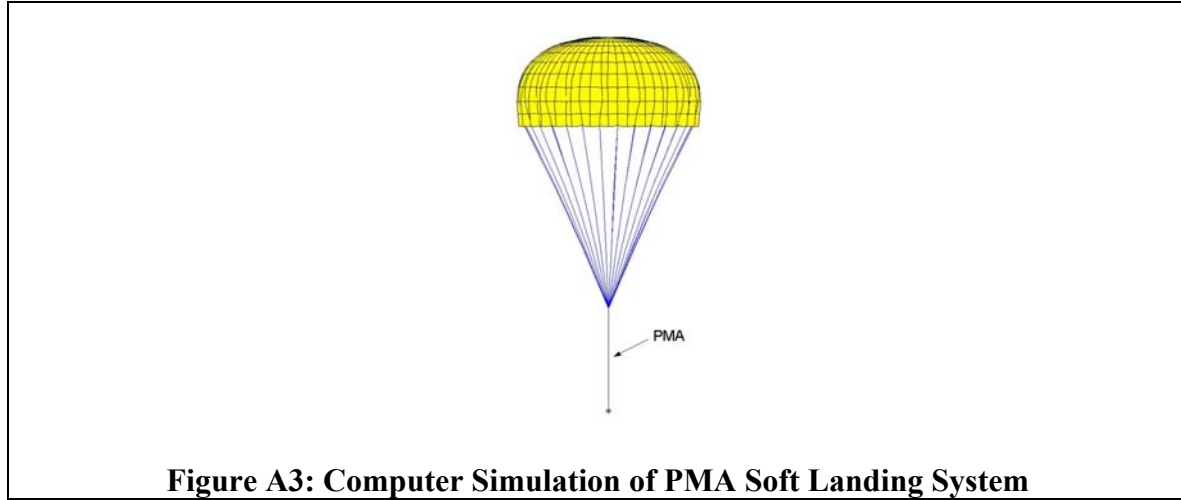
- **Simulation of Foreign Body Impact with an Inflated Canopy**

In this simulation, a solid rigid body impacts an inflated canopy with a specified initial velocity. As shown in Figure A2a, the rigid body is suspended as a pendulum to approximate the motion of second payload attached to a neighboring parachute. Interaction and contact between multiple parachutes is a common occurrence during mass deployments that can result in collapse and failure of one or more parachutes. To date, the study of such phenomena has been extremely limited. The CSD model developed under this project provides an effective tool to study this complex problem



- **Simulation of a Pneumatic Muscle Actuator (PMA) Soft Landing System**

New soft landing airdrop systems that utilize PMAs as a retraction device have recently been developed and are currently being evaluated [6]. In these systems, a PMA is attached between the confluence point and payload, as shown in Figure A3. Prior to impact, the PMA is pressurized and contracts, which significantly reduces the payload impact velocity. As shown in Figure A3, the new PMA element developed under this project provides a simple yet accurate tool to model the mechanical behavior of a PMA incorporated within a parachute structural model.



- **Simulation of a Dynamic Payload Reorientation Problem**

In this simulation, a parachute payload is dynamically reoriented from an initially vertical position to a horizontal position during terminal descent. The Sliding Cable Elements (SCE) developed under this project can easily be used within a general parachute model to accurately model this type of operation. Figures A4a and A4b show the system configuration at two times close to the initial and final times, respectively. The interaction between the payload and canopy dynamics is fully captured in this model.

